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Abstract

This study examined whether during childhood, the parameters for the range of motion had more influence on vertical jump height than parameters for application of force. Countermovement jumps performed by 36 girls aged between 5 to 8 years and 20 adult females were examined using force platform analysis. Multiple regression analysis of the data indicated that the parameters for the range of motion had more influence on jump height than the parameters for application of force. This was demonstrated by standardized coefficients for range of motion which were higher than the standardized coefficients for application of force. Although this trend was observed in both groups, the influence of the range of motion was relatively greater in prepubescent girls than in adult females. The present results suggest that prepubescent girls increased their jump height by increasing the range of motion over which force is applied.

Key words: countermovement jump, development, prepubescent girls

## Introduction

In children, the vertical jump is one of the most common skills in sports and games and the most common way to evaluate performance in this activity is by measuring the height jumped. Numerous studies have shown progressive increases in jumping height from childhood to adolescence (Malina, Bouchard, & Bar-Or, 2004; Van Praagh & Doré, 2002; Wang, Lin, & Huang, 2004). During the fundamental movement phase of development which occurs at approximately 4 to 7 years, children acquire skills such as running, jumping, kicking, throwing, and catching (Gallahue & Ozmun, 2006). In this phase, boys and girls increase their strength and jumping height without differences between sexes (Malina et al., 2004). From 11 years old to adulthood, boys generally attain a greater height in the vertical jump than girls (Taylor, Cohen, Voss, & Sandercock, 2010; Temfemo, Hugues, Chardon, Mandengue, & Ahmaidi, 2009). Subsequently, jumping performance continues to increase with respect to age in boys until 19 years old (Branta, Haubenstricker, & Seefeldt, 1984; Taylor et al., 2010), however, for girls, jumping height only increases until the pubertal stage before reaching a plateau, or possibly declining in performance (Loko, Aule, Sikkut, Ereline, & Viru, 2000; Taylor et al., 2010). This gender difference could be due to girls not experiencing a spurt in neuromuscular developmental during puberty (Quatman, Ford, Myer, & Hewett, 2006).

While many studies explain how the increases in jump height during development are related to changes in anthropometry or muscle force (e.g., Temfemo et al., 2009; Taylor et al., 2010) relatively few studies have focused on the effects of changes in the movement patterns (i.e., technique) on jumping height during development (Clark, Phillips, & Petersen, 1989; Harrison, & Gaffney, 2001; Hudson, 1986; Jensen, Phillips, & Clark, 1994; Wang et al., 2004). Some research on adults has shown that to increase the vertical jump performance, an optimal sequence of movement is required as well as an effective use of the stretch-shortening cycle (SSC), (Bobbert, Gerritsen, Litjens, & Van Soest, 1996; Bobbert & Van Ingen Schenau, 1988). Some studies have suggested that children and adults utilize the SSC equally well to enhance their performance in the vertical jump although the variability of SSC contribution is greater in children compared to the adults (Gerodimos et al., 2008; Harrison & Gaffney, 2001). The reductions in variability are a general characteristic of motor development and learning (Newell & Corcos, 1993). On the other hand, other studies conclude that there are no differences in the coordination of vertical jump movements between children and adults although there are differences in the amplitude and velocity of motion (Clark et al., 1989; Jensen et al., 1994). Both children and adults show the same degree of synchronization in the timing of the maximum segmental velocities during the extension phase (Clark et al., 1989; Hudson, 1986; Jensen et al., 1994), but there are differences in the magnitude of the angles, displacements, joint ranges, or peak joint extension velocities used during the jump. The projection angle at take-off (calculated from the horizontal and vertical speed of the athlete's centre of mass) has been found to be significantly smaller in children compared with adults which could be the result of incomplete leg extension before take-off due to insufficient strength or postural control deficiencies (Jensen et al., 1994). Moreover, the range of motion of the lower limb joints is smaller in children than in adults in both the downward and upward phases of the jump (Clark et al., 1989; Jensen et al., 1994; Wang et al., 2004). This lower range of motion could shorten the time for force application and based on the application of Newton's Second Law, this could decrease the impulse generated, resulting in lower take-off velocity and jump height. At take-off, children generally have a smaller extension in the lower limbs joints compared with adults (Jensen et al., 1994; Wang et al., 2004). During the jump the legs should produce as much energy as possible before take-off and an incomplete extension of the legs could decrease the propulsive range of motion, thereby reducing the energy produced and resulting in a decrement in jump performance. Differences in movement amplitude between children and adults in the downward movement phase have also been observed and shown to be larger than the differences in the upward phase (Clark et al., 1989; Jensen et al., 1994; Wang et al., 2004). Wang et al. (2004) suggested that a smaller depth of countermovement in conjunction with lower stiffness of the lower limb might decrease the pre-stretch and SSC in children. This smaller downward displacement may result from the children's lack of ability to control large segments, such as the trunk, due to relative immaturity in postural control (Clark et al., 1989; Jensen et al., 1994).

While previous studies have indicated significant differences in the range of movement between children and adults, it is not clear whether these differences are important in determining the height of the jump (Clark et al., 1989; Jensen et al., 1994; Wang et al., 2004). Nor is it clear if the range of movement has more influence on jumping performance than other parameters related to application of force. For a better understanding of child development, it is necessary to identify the parameters that have most influence on the height of the jump. Consequently, the aim of this study was to ascertain whether during childhood, the parameters for the range of motion (i.e., the technique related variables) had more influence on jump height than parameters for application of force (i.e. the strength related variables). Therefore, this study compared the influence of both technique and strength related parameters on vertical jump height in prepubescent girls and adult females.

## Methods

### Participants

The study had obtained ethical approval from the University research ethics committee. All adult participants and parents/guardians of prepubescent participants signed informed consent forms before participating in the study. The participants (n= 56) were divided into two groups: adults (n= 20) and prepubescent girls (n= 36). The adult group consisted of 20 females aged 22.3 ± 3.1 years (mean ± SD), with a mass of 61.2 ± 7.4 kg and a height of 1.63 ± 0.06 m. The prepubescent girls' group consisted of 36 females aged between 5 to 8 years old (6.8 ± 1.3 years-old) with a mass of 23.1 ± 5.3 kg and a height of 1.19 ± 0.09 m. The prepubescent girls were chosen in this age range, since this approximates the fundamental movement phase where the development of a mature vertical jumping sequence is normally achieved (Gallahue & Ozmun, 2006). The adults recruited were physically active and the girls trained in acrobatic gymnastics twice per week. No participants had any past history of nervous system or muscular dysfunction.

### Vertical jumping test

Participants were instructed to perform counter-movement jumps (CMJ) on a portable force platform (Quattro Jump®, Kistler Instrumente AG, Winterthur, Switzerland). Before each test, the participants performed 10 minutes of warm-up activity which included a brief period of low-intensity aerobic exercise, some short duration static stretching exercises and one set of 5 sub-maximal jumps. Since all participants were physically active and regularly performed activities including jumping, a short familiarisation session of was sufficient to ensure the participants could complete the jumping tasks to a satisfactory level.  Force data were sampled at 500 Hz and the duration of data collection was 5 seconds. The instructions for each participant were standardised. They included a detailed verbal explanation and a physical demonstration by the experimenter. The importance of jumping as high as possible was emphasised. During the CMJ, the participants initially stood upright and stationary for at least 2 seconds during which body weight was recorded, then squatted to a self-selected depth and jumped immediately as high as possible without pausing. For all jumps, participants retained the “hands on hips” position until the landing phase. Three successful jumps were recorded for each participant, with at least 2 minutes of rest between jumps. The average of the three successful jumps was used for analysis (Bland & Altman, 1994).

Analysis

The vertical component of centre of mass (CoM) velocity was estimated using the impulse method (Linthorne, 2001). Net impulse was obtained by integrating the net vertical ground reaction force, from 2 s prior to the first movement of the participant (Street, McMillan, Board, Rasmussen, & Heneghan, 2001), using the trapezoid method (Kibele, 1998). Subsequently, vertical CoM velocity was calculated by dividing the net impulse by the participant's body mass. Vertical CoM displacement was derived by numerically integrating the vertical CoM velocity.

To facilitate data analysis, five events were defined during the CMJ (see Figure 1). The first event was the start of the movement, which was identified on the recommendations of Street et al. (2001). This event was detected by inspecting the force-time records to identify the first instant where the vertical ground reaction force deviated above or below body weight (BW) by more than one threshold. The threshold was defined as 1.75 times the peak residual found in the 2 seconds of the BW averaging period. A backward search was then performed until vertical ground reaction force passed through BW. The second event was the instant maximum downward velocity of the CoM. The third event was the instant of zero velocity of the CoM. The fourth event was the instant of maximum upwards velocity of CoM. The last event was the instant of take-off which was defined as the first intersection of vertical ground reaction force with an offset threshold where, the threshold was determined by adding the average flight time (i.e., 0.4 seconds) and the peak residual to the offset (Street et al., 2001). Four phases were defined based on these events (Figure 1).

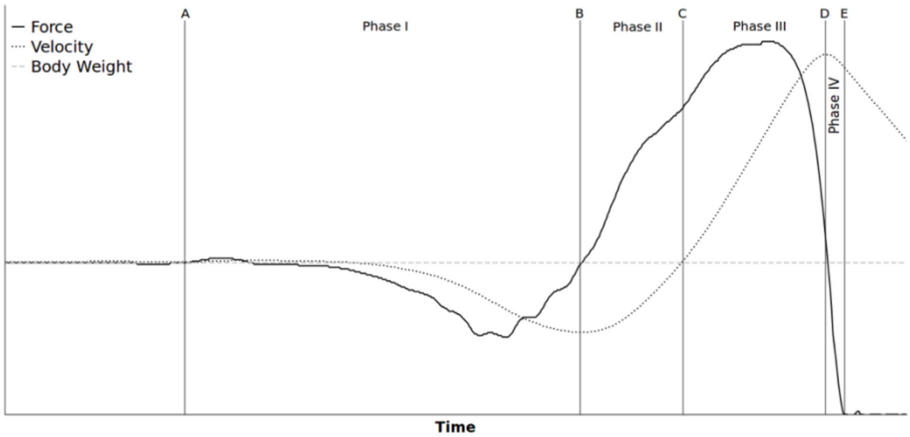


**Figure 1**. Identification of the phases and events during the countermovement jump. A: start of movement. B: instant of maximum downward velocity of CoM. C: instant of zero velocity of the CoM. D: instant of maximum upwards velocity of CoM. E: take-off.

After identifying the phases, the kinematics and kinetics variables shown in Table 1 were calculated for each phase. The force variables were normalized to BW while the distance variables were normalized to body height (BH). The variables assigned to one of the following 3 groups: range of movement, average force and instantaneous force. This was done to show which group of variables had most influence on the height jumped.

**Table 1**. Description of the calculated variables in the study. The performance and range of movement parameters are normalised to body height (BH), force parameters are normalised to body weight (BW) and the rates of force parameters are expressed in BW·s$^{-1}$.

| Variable group | Variable | Description | Unit |
|---|---|---|---|
| | $h_{max}$ | Maximal height of CoM achieved during the flight | BH |
| | $h_{flight}$ | Vertical distance travelled by CoM during the flight | BH |
| | $h_{takeoff}$ | Height of CoM achieved at take-off | BH |
| Range of movement variables | $L_I$; $L_{II}$; $L_{III}$; $L_{IV}$ | Vertical displacement of CoM during each phase | BH |
| Average force variables | $F_I$; $F_{II}$; $F_{III}$; $F_{IV}$ | Average vertical ground reaction force during each phase | BW |
| Instantaneous force variables | $F_{min}$ | Minimal vertical ground reaction force during $L_I$ | BW |
| | $F_{v=0}$ | Vertical ground reaction force at the instant vertical velocity of CoM was 0 | BW |
| | $F_{max}$ | Maximal vertical ground reaction force during $L_{III}$ | BW |
| | $ECC_{RFD}$ | Gradient of the force-time curve from the initiation of the eccentric phase to the end of the eccentric phase | BW·s$^{-1}$ |
| | $CON_{RFD}$ | Gradient of the force-time curve from the initiation of the concentric phase to $F_{max}$ | BW·s$^{-1}$ |

## Statistical analysis

Statistical analyses were conducted using SPSS version 18.0. Means and standard deviations of each participant group were computed for all the measured variables. Normality of the data sets was verified using the Shapiro-Wilk test. If the data were normally distributed within groups, an independent samples *t*-test was used to test the differences between adults and prepubescent females. If the data were not normally distributed, then a Mann-Whitney *U*-test was used. The magnitude of differences between groups was expressed as standardized mean differences (Cohen d, effect sizes). The criteria to interpret the magnitude of the effect size were: trivial = 0.00 – 0.19, small = 0.20 – 0.59, moderate = 0.60 – 1.20, and large >1.20 (Hopkins, 2004). Two separate stepwise (backward) multiple regression analyses were used:

(1) with $h_{max}$ as dependent variable and range of movement parameters and average force parameters as independent variables

(2) with $h_{max}$ as dependent variable and range of movement parameters and instantaneous force parameters as independent variables

## Results

The normalised mean ± SD values for the adults and prepubescent groups are presented in Table 2, as well as the statistical significance of differences between groups ($P < 0.05$). The results show that jump height was significantly higher in adults than in prepubescent girls. Flight height was also significantly higher in adults than in prepubescent girls but there was no statistically significant difference in $h_{takeoff}$ between the two groups. During the downward movement, the first phase was significantly higher in adults than prepubescent girls, but during upward movement, the last phase was significantly higher in prepubescent girls than adults. For average force variables, only $F_{IV}$ was significantly lower in adults than prepubescent girls, whereas there was no significant difference in other average force variables. The instantaneous force variables were similar in both groups, except for $CON_{RFD}$ which was significantly higher in prepubescent girls than adults. The effect sizes using Cohen's d showed large difference in the displacement y average force in the last phase, moderate differences in maximum and flight height, and $CON_{RFD}$, and only trivial or small differences for all other variables.

**Table 2**. Normalised means ± standard deviations of the variables studied in the jump. * Indicates $P$ < 0.05.

| Variable | Adults ($N$ = 20) | Prepubescent Girls ($N$ = 36) | Cohen's $d$ |
|---|---|---|---|
| $h_{max}$ (BH) | 0.23* ± 0.03 | 0.19 ± 0.03 | 1.11 |
| $h_{flight}$ (BH) | 0.15* ± 0.03 | 0.12 ± 0.02 | 1.07 |
| $h_{takeoff}$ (BH) | 0.08 ± 0.01 | 0.07 ± 0.01 | 0.48 |
| Range of movement variables | | | |
| $L_I$ (BH) | 0.11* ± 0.02 | 0.09 ± 0.02 | 0.63 |
| $L_{II}$ (BH) | 0.07 ± 0.02 | 0.07 ± 0.03 | -0.19 |
| $L_{III}$ (BH) | 0.21 ± 0.03 | 0.19 ± 0.05 | 0.57 |
| $L_{IV}$ (BH) | 0.04* ± 0.01 | 0.05 ± 0.01 | -1.66 |
| Average force variables | | | |
| $F_I$ (BW) | 0.82 ± 0.07 | 0.80 ± 0.07 | 0.27 |
| $F_{II}$ (BW) | 1.56 ± 0.20 | 1.58 ± 0.27 | -0.08 |
| $F_{III}$ (BW) | 1.94 ± 0.17 | 1.99 ± 0.27 | -0.2 |
| $F_{IV}$ (BW) | 0.45* ± 0.03 | 0.48 ± 0.03 | -1.24 |
| Instantaneous force variables | | | |
| $F_{min}$ (BW) | 0.56 ± 0.16 | 0.48 ± 0.16 | 0.54 |
| $F_{v=0}$ (BW) | 2.10 ± 0.29 | 2.06 ± 0.43 | 0.10 |
| $F_{max}$ (BW) | 2.20 ± 0.21 | 2.30 ± 0.37 | -0.33 |
| $ECC_{RFD}$ ($BW \cdot s^{-1}$) | 1.63 ± 0.66 | 2.03 ± 1.50 | -0.35 |
| $CON_{RFD}$ ($BW \cdot s^{-1}$) | 1.70* ± 0.93 | 4.16 ± 3.34 | -1.01 |

Table 3 shows the calculated coefficients of variation (CV) and associated 95% confidence limits for each variable for both adults and prepubescent girls. Although the CV scores were under 10% in most of the variables analysed, they were always lower in adults. The highest CV scores were found in $ECC_{RFD}$ and $CON_{RFD}$ for both groups. Table 4 shows the results of multiple regression analysis with maximum height as the dependent variable and the parameters for the range of motion and for average of force as independent variables. Standardized regression coefficients provide one method for comparing the relative influences the parameters for the range of motion and the application of force on the jump height. For both groups, $L_{III}$ had greater influence on maximum height than the rest of parameters for the range of motion and the parameters for average of force. In prepubescent girls, the standardized coefficient for $L_{III}$ was three times higher than the standardized coefficient for $F_{III}$. Whereas in adults the ratio of these standardized coefficients was only 1.6.

**Table 3**. Coefficients of variation (CV) and associated 95% confidence limits for the variables studied during the countermovement jump.

| | Adults ($N = 20$) | | | Prepubescent Girls ($N = 36$) | | |
|---|---|---|---|---|---|---|
| | | 95% Confidence limits | | | 95% Confidence limits | |
| Variable | CV% | Lower | Upper | CV% | Lower | Upper |
| $h_{max}$ (BH) | 3.2 | 1.8 | 4.6 | 7.0 | 5.1 | 9.0 |
| $h_{flight}$ (BH) | 4.3 | 2.7 | 5.8 | 8.0 | 6.1 | 9.8 |
| $h_{takeoff}$ (BH) | 6.7 | 5.1 | 8.2 | 12.9 | 9.0 | 16.8 |
| Range of movement variables | | | | | | |
| $L_{I}$ (BH) | 12.4 | 6.4 | 18.5 | 12.6 | 10.1 | 15.2 |
| $L_{II}$ (BH) | 18.1 | 12.3 | 24.0 | 19.7 | 15.8 | 23.7 |
| $L_{III}$ (BH) | 6.6 | 4.0 | 9.1 | 9.6 | 7.5 | 11.7 |
| $L_{IV}$ (BH) | 8.8 | 6.4 | 11.1 | 8.3 | 6.3 | 10.4 |
| Average force variables | | | | | | |
| $F_{I}$ (BW) | 5.6 | 4.4 | 6.8 | 8.1 | 6.2 | 10.0 |
| $F_{II}$ (BW) | 4.7 | 3.5 | 6.0 | 6.8 | 5.2 | 8.3 |
| $F_{III}$ (BW) | 3.5 | 1.9 | 5.2 | 5.3 | 4.1 | 6.5 |
| $F_{IV}$ (BW) | 5.5 | 3.9 | 7.0 | 4.9 | 4.0 | 5.8 |
| Instantaneous force variables | | | | | | |
| $F_{min}$ (BW) | 16.5 | 8.3 | 24.7 | 21.8 | 16.9 | 26.6 |
| $F_{v=0}$ (BW) | 5.1 | 3.5 | 6.8 | 10.2 | 7.9 | 12.4 |
| $F_{max}$ (BW) | 3.9 | 2.3 | 5.5 | 7.1 | 5.6 | 8.6 |
| $ECC_{RFD}$ ($BW \cdot s^{-1}$) | 20.6 | 14.1 | 27.1 | 39.1 | 32.8 | 45.5 |
| $CON_{RFD}$ ($BW \cdot s^{-1}$) | 44.5 | 30.4 | 58.7 | 35.6 | 27.4 | 43.9 |

**Table 4**. Multiple regression to predict the influence of the parameters for the range of motion and the parameters for average force on height jump. * Indicates $P$ < 0.05. ** indicates $P$ < 0.01.

| Independent variables | Unstandardised coefficients | | Standardized coefficients beta | t-test |
|---|---|---|---|---|
| | B | Std. Error | | |
| Adults $R^2 = 0.927$, $F = 21.717^{**}$ | | | | |
| (Constant) | 0.000 | 0.151 | | -0.001 |
| $L_{III}$ | 1.984 | 0.301 | 1.980 | $6.582^{**}$ |
| $F_{III}$ | 0.224 | 0.027 | 1.264 | $8.202^{**}$ |
| $F_{II}$ | −0.150 | 0.052 | -0.968 | $-2.880^{*}$ |
| $L_{II}$ | −1.524 | 0.383 | -0.935 | $-3.977^{**}$ |
| $F_{I}$ | −0.294 | 0.125 | -0.644 | $-2.352^{*}$ |
| $L_{I}$ | −0.773 | 0.381 | -0.439 | -2.028 |
| (Constant) | 0.072 | 0.0810.985 | | |
| $L_{III}$ | 1.826 | 0.195 | 3.075 | $9.382^{**}$ |
| $L_{II}$ | −1.459 | 0.177 | -1.769 | $-8.227^{**}$ |
| $L_{I}$ | −1.213 | 0.223 | -1.039 | $-5.439^{**}$ |
| $F_{III}$ | 0.098 | 0.018 | 0.927 | $5.427^{**}$ |
| $F_{II}$ | −0.062 | 0.019 | -0.606 | $-3.204^{**}$ |
| $F_{I}$ | −0.156 | 0.055 | -0.398 | $-2.858^{**}$ |
| $L_{IV}$ | 0.539 | 0.394 | 0.125 | 1.371 |

Table 5 shows the results of multiple regression analysis with maximum height as the dependent variable and the parameters for the range of motion and the parameters for instantaneous force as independent variables. Again, $L_{III}$ was the parameter with greatest influence on maximum jump height in both adults and prepubescent girls. In prepubescent girls the grade influence was $L_{III}$ (greatest) followed by $L_{II}$ and $F_{max}$ but in adults the grade of influence was $L_{III}$ (greatest) followed by $F_{max}$ and $L_{II}$. In prepubescent girls, the relative influence of $L_{III}$ was 2.5 times greater than the most influential variable related to the application of force which was maximal force. In contrast, this ratio decreased to 1.8 in adults.

**Table 5**. Multiple regression to predict the influence of the parameters for the range of motion and the parameters for instantaneous force on height jump. * Indicates $P < 0.05$. ** indicates $P < 0.01$.

| Independent variables | Unstandardised coefficients | | Standardized coefficients beta | t-test |
|---|---|---|---|---|
| | B | Std. Error | | |
| Adults $R^2 = 0.921$, $F = 19.393^{**}$ | | | | |
| (Constant) | -0.133 | 0.062 | | -2.159 |
| $L_{III}$ | 1.608 | 0.351 | 1.669 | $4.577^{**}$ |
| $F_{max}$ | 0.130 | 0.035 | 0.907 | $3.747^{**}$ |
| $L_{II}$ | −1.458 | 0.393 | -0.858 | $-3.705^{**}$ |
| $L_{I}$ | −1.037 | 0.424 | -0.608 | $-2.446^{*}$ |
| $CON_{RFD}$ | −0.020 | 0.003 | -0.582 | $-6.191^{**}$ |
| Prepubescent $R^2 = 0.716$, $F = 8.524^{**}$ | | | | |
| (Constant) | −0.069 | 0.060 | | -1.150 |
| $L_{III}$ | 1.709 | 0.242 | 2.877 | $7.068^{**}$ |
| $L_{II}$ | −1.460 | 0.241 | -1.770 | $-6.054^{**}$ |
| $F_{max}$ | 0.087 | 0.023 | 1.147 | $3.814^{**}$ |
| $L_{I}$ | −1.068 | 0.297 | -0.914 | $-3.593^{**}$ |
| $ECC_{RFD}$ | −0.008 | 0.007 | -0.435 | -1.240 |
| $F_{v=0}$ | −0.028 | 0.025 | -0.429 | -1.105 |
| $F_{min}$ | −0.051 | 0.029 | -0.281 | -1.743 |
| $L_{IV}$ | 0.901 | 0.546 | 0.208 | 1.650 |

## Discussion

Much of the scientific literature on the development of the vertical jump has focused on boys with relatively few studies on prepubescent girls. It is known that females demonstrate a continuous rise in fat mass during puberty (Beunen & Malina, 1988) in conjunction with the tendency to reduce the engagement in sport and physical activity after the age of 12 years (Biddle, Whitehead, O'Donovan, & Nevill, 2005) and this may explain why in some studies the jumping performance of prepubescent girls does not increase significantly beyond the age of 12 years. This study attempted to describe the influence of range of motion and the application of force on the height jumped in prepubescent girls, and to compare whether their influence on the height jumped is maintained in adulthood.

The results of the regression analysis showed that the parameters that described the range of motion accounted for more variation in $h_{max}$ and had more influence on jump height than the parameters for application of force. Although this was observed in both groups, the influence of the range of motion was greater in prepubescent girls than in adults. This difference between prepubescent and adult groups may indicate that once that the fundamental movement pattern for jumping has been established, the predominant influence of range of motion on performance decreases as strength related parameters become more predominant at later stages of development.

The importance of range of motion on jump height has been described in previous studies which showed that performance may increase with increasing the distance over which force can be generated. The biomechanics are logical as an increase in the range of joint motion during which force is generated can increase the net impulse during the upward movement phase and consequently improve the velocity at take-off (Alexander, 1995; Bobbert et al., 1996; Samozino, Morin, Hintzy, & Belli, 2010). This has also been confirmed by Wang et al. (2004), who observed that the greatest jump height of adults compared with children could be due to a greater range of motion. Similary, Ugrinowitsch et al. (2007), found differences in the displacement of the CoM during the jump between a group of well-trained athletes and untrained individuals with the well-trained athletes being able to move their bodies over a longer distance compared with the untrained group. Furthermore, Laffaye et al. (2005), observed that increases in jump height in a one-leg vertical jump were accompanied with decreases in contact time and leg stiffness as well as small increases in maximum vertical force and large increases in leg shortening.

The learning process of the jump could provide a rationale for the greater influence of range of motion in children compared with adults. Some literature (e.g., Strohmeyer et al., 1991) has suggested that when a child initially learns a skill, they “freeze” the degrees of freedom of movement to facilitate the control. After attaining initial control, the child is able to increase the range of movement of joints enabling successful and consistent performance. The results obtained in this investigation could be explained by this principle in motor learning.

It is widely accepted that maximal jump height in males is greater in adults than prepubescent children (Wang et al., 2004) and the results of this investigation confirmed a similar trend in females. The comparison of $h_{max}$ in girls and adult females showed that adult females on average, jumped 21% higher than girls (Cohen's d = 1.11). This increase in $h_{max}$ was due mainly to a greater distance travelled by CoM during flight rather than a higher position of the CoM at takeoff. These results were similar to those previously reported (Gerodimos et al., 2008; Taylor et al., 2010; Temfemo et al., 2009), who observed that both boys and girls had higher jump height in adolescence than in childhood.

The results of the analysis of the force and movement of the CoM showed that the greatest differences were found in the last phase of the jump. During this phase, the girls applied 6.7% more force and the CoM travelled 25% further than adults, the effect size analysis indicated that these were large effects. Inspection of the literature to date, indicated that no other studies have compared these parameters in prepubescent children and adults using similar methodologies, however the results contrast with other studies examining developmental trends in the kinematics of the vertical jump in children (Jensen et al., 1994; Wang et al., 2004). These studies observed an incomplete extension of the lower limbs during the upward phase of the jump and suggested that this was due to insufficient strength leading to a reduction in the pushing distance. Since phase IV begins when the ground reaction force is less than body weight, this suggests that a relative weakness in the final knee extension or ankle plantarflexion could cause phase IV to begin earlier in the jump resulting in an increase in COM displacement during this phase. Further studies are needed to evaluate the interaction between the kinematics and kinetics of the lower limbs during the jump in childhood.

During the upward movement phase of the jump, prepubescent girls were found to have significantly higher rates of force development, ($CON_{RFD}$) compared to adults however, despite these higher values, prepubescent girls jumped significantly lower than adults. Based on these results, it appears that the ability to develop force quickly is not sufficient to ensure a high level of performance in the vertical jump. This finding contrasts with the conclusion of Ritcher et al. (2010), who stated that the maximum rate of force development appeared to increase with the maturation. The reason for the contrasting conclusion, however, appears to be more related to methodological differences rather than conflicting results. In this investigation the force variables were divided by BW for each participant in order to reduce the influence of differences in size, while Ritcher et al. (2010) did not use any normalisation procedures, and this could explain the different results. The importance of normalising scores to account for body size differences in motor development studies has been emphasised by Barret and Harrison (2002). Only one variable during the downward phase of the jump was different between the groups. During the first part of the downward movement, the CoM displaced further in adults than in prepubescent girls. This result is consistent with previous studies (Clark et al., 1989; Jensen et al., 1994; Wang et al., 2004), which suggested that jump technique evolves towards a greater depth of countermovement in the more advanced stages of development.

The results of this study showed higher coefficients of variation in prepubescent girls than adults in most of the variables analyzed. This supports the findings of previous studies on development in vertical jump. Harrison and Gaffney (2001) reported that children were less consistent in their vertical jumping performance than adults and suggested that children had less well-developed ability in the jump compared to adults. It is well established that the motor patterns of less skilled individuals may be more variable than highly skilled performers (Newell & Corcos, 1993). Research has shown that during the development and learning of a motor task, children learn to suppress movement variability as their performance is enhanced due to the practice (Button, MacLeod, Sanders, & Coleman, 2003; Fleisig, Chu, Weber, & Andrews, 2009; Schorer, Baker, Fath, & Jaitner, 2007). In this study, the greatest amount of variability was observed in $ECC_{RFD}$ and $CON_{RFD}$ for both prepubescent girls and adults. This is consistent with previous studies which concluded that the rate of force developed is an unstable and highly variable parameter in adults (McLellan, Lovell, & Gass, 2011) and children (Richter et al., 2010).

## Conclusion

This study has demonstrated the importance of range of motion in the child's development during the fundamental movement phase. The regression analysis showed that in prepubescent girls $L_{III}$ had the greatest influence on jumping height compared with all other variables studied. In particular, the ability to increase the pushing distance seems to be the most important parameter to enhance vertical jump performance during fundamental movement phase in girls. The results of this study suggest that training strategies to increase jump height in prepubescent girls should focus on improving the distance over which the performer applies a force greater than body weight. Therefore In addition, in the early stages of development, the training should be focused on increasing range of motion , to further and in adulthood the training should focus on develop the ability to produce force throughout the along this range of motion. It is recommended that future studies should seek to verify if the results of this research are valid for males as well as females and to determine which joint actions have the greatest influence on performance during the jump.

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